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Flexibility Monitoring of Offshore Jacket Platforms

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ABSTRACT

The new concept of Flexibility Monitoring, emphasizing the detection of fundamental vibration mode shapes, is an outgrowth of a general study of vibration monitoring for offshore oil and gas platforms. Its theoretical promise has been borne out in practice over the past several years in laboratory and field tests. The method is useful for underwater damage detection and, more generally, for identification of flexibility parameters of the structural dynamic mathematical model. Blind failure conditions involving removal of a K-brace section and foundation stiffness change were correctly identified in a government-run laboratory test program. The brace removal was located in the correct bay and face of the model platform. Follow-on special testing of the model further demonstrated the theoretical expectation that diagonal severance is clearly distinguishable from both foundation flexibility and deck mass changes. It was shown that a very simple mathematical model provides similar sensitivity trends to those observed experimentally. Field experiments on the Shell Cognac and Chevron Garden Banks platforms have indicated that the necessary high quality data can be obtained from ambient acceleration measurements at underwater corner positions of a working platform. Continued development is warranted. Directions for future work are outlined.

INTRODUCTION

With Flexibility Monitoring, diagnosis of potential failure is based primarily on detecting the deflection shapes of the three fundamental vibration modes (two sway modes and one torsion). Advantage is taken of the predominant shear beam behavior of a steel jacket platform and the approximate equivalence between the fundamental mode shapes and the static deflection shapes due to corresponding deck loading. The concept can be effective for examining changes in directional shear flexibilities of individual jacket framing bays and of the foundation. An important consequence is that mass changes are deemphasized. The original "global mode monitoring" concept, with its emphasis on frequency shifts of the lower modes, typically provides less capability to detect and locate failure, because it is less sensitive to jacket damage (for reasons of high overall redundancy) and is a much poorer discriminator of the cause of change: jacket flexibility, foundation flexibility, or mass.[1]

Field application of Flexibility Monitoring is visualized as involving temporary deployments of accelerometer packages placed down special, abovewater accessible, instrument chutes. The chutes are located on corner legs of a platform and extend down to the foundation. Ambient vibration data are acquired from a sequence of package positionings at the upper and lower levels of the jacket bays simultaneously with acquisition of deck corner accelerations. The acquisition system is optimized to detect the fundamental modes from ambient vibration, generally in the frequency range of 1/4 to 1 Hz. Optimized experimental apparatus and procedures are required to yield accurate Flexibility Parameters. These key parameters are equal to average horizontal deflection across each bay, normalized to the corresponding horizontal deflection in the abovewater portion of the platform. With $\bar{X}_i$ denoting the average deflection of level i, the Flexibility Parameter depicted in Fig. 1 is defined as:

$$\Delta = \frac{\bar{X}_2 - \bar{X}_3}{\bar{X}_0 - \bar{X}_1} \quad \text{.................................(1)}$$

Three such parameters, one for each direction of sway and one for torsion, are determined for each bay. The corresponding three foundation lateral deflections yield foundation shear flexibility parameters, and vertical foundation deflections yield rotational flexibility parameters.

References and illustrations at end of paper.

ROUND ROBIN PROGRAM

This program was established by the government to evaluate the applicability of specific techniques for structural monitoring and inspection. The purpose was to assist in planning future research in nondestructive examination (NDE) on the part of the Mineral Management Service (MMS) of the U.S. Department of the Interior, and the Office of Naval Research (ONR).

Evaluation of several vibration-based methods was to be based on the ability to detect blind damage and nondamage changes in a simplified 1:13.8-scale, welded tubular model of a four-leg platform (see Fig. 2). The simplifications included the absence of piles or conductors, realistic foundation, and immersion in water. The first author acted as the advocate for a subset of approaches representing the "frequency response method." The first approach was patterned after the original global mode monitoring concept and involved detection of the fundamental modes at abovewater positions. The second approach, Flexibility Monitoring, involved detection of fundamental mode shapes, both abovewater and at underwater bracing levels. The final "local mode" approach, employed known abovewater random forcing and abovewater responses at higher frequencies to detect the fundamental family of out-of-face modes of the K-brace sections.

Baseline testing was performed to evaluate and refine the test set up and data analysis conduct, and to provide reference data for the structure in an undamaged state. Detailed procedures were provided to the testing laboratory (at the NASA Goddard Space Flight Center), and four blind-mode damage scenarios were run. Prerequested data were transmitted to the advocates and, in return, diagnoses of damage were provided to the neutral agent, Dr. R. Dame of the Mega Engineering Corporation. The requested specific responses included a determination of damage presence along with a statement of confidence, location of any damage, and commentary.

The four damage scenarios were: (1) one leg disconnected from the rigid foundation, (2) half-through cuts at the ends of one horizontal brace at the lowest level, (3) removal of one K-brace in the lowest bay, and (4) a no-change-from-baseline case. Each of the three evaluation approaches in the frequency-response series proved to be useful. Scenarios (1), (3), and (4) were correctly identified by global mode monitoring. Also, this method correctly led to the conclusion of no significant overall strength loss for scenario (2). Precise location of the diagonal failure in scenario (3), as well as considerable corroborating evidence for scenarios (1) and (4), were provided by Flexibility Monitoring. Since the partial failure of a horizontal in scenario (2) did not affect jacket shear flexibility, it was undetectable by global mode monitoring or by Flexibility Monitoring. The local mode approach, however, did yield a correct diagnosis of scenario (2), with 50% confidence and with the location properly given as most probably at the lowest level. The weakness of the observations for this scenario and the inability to discriminate mass changes on the bracing (such as from marine growth) led to the judgment of 50% confidence. A thorough presentation of the authors' findings has been reported to the MMS, the sponsor.[2] A report of the overall program is under preparation by Mega Engineering.

Our major conclusion was that the Round Robin experience,[2] as well as favorable mathematical sensitivity results and our prior field test experience on the SP-62C platform,[3,4] all indicate that Flexibility Monitoring is a most attractive technique for field evaluation.

ADDITIONAL MODEL TESTING

Because of the considerable promise evidenced by Flexibility Monitoring, a follow-on opportunity was provided by the Mineral Management Service to conduct additional tests using the Round Robin model. The effort had two purposes: (1) to check out and refine procedures for a possible future field test and (2) to obtain more complete experimental evidence of the sensitivities of the method.

With regard to preparation for field testing, duplication of the test conduct and data analysis procedures that would be employed on an offshore platform was desired. This involved the acquisition of all data necessary to determine each Flexibility Parameter; namely, a total of eight acceleration records acquired simultaneously at opposite corners of each of four platform levels: deck, level 1, and the levels above and below the bay being monitored. The equipment employed were those planned for a field test and included specially developed four-channel analog summers to produce each bay's shear deflection and the corresponding abovewater shear deflection, and a portable FFT analyzer to transform these two analog signals into the Flexibility Parameter by transfer function analysis. At the same time, the data were independently processed using the analysis system in the laboratory (a minicomputer-based digital processing system) thus enabling direct comparisons of derived Flexibility Parameters from the two systems. This was done for the initial test configurations, and it was shown that the planned field procedures and equipment provided essentially the same results as did the laboratory system.

As to the study of sensitivities, the following model configurations were tested in this sequence:

1. Baseline model on soft foundation. Rubber padding was employed to "float" the platform leg bottom plates relative to the seismic slab. An 8 to 9% reduction in the fundamental sway natural frequencies was achieved relative to the hard foundation.

2. Added deck mass with soft foundation. A 26.5-lb lead block was clamped to a side of the deck, as depicted in Fig. 2. This yielded an approximate 50% increase to the deck mass and provided strong inertial coupling between Y sway and torsion. A 14 to 15% reduction in the

fundamental sway natural frequencies was realized.

3. Severed diagonal with soft foundation. With the added deck mass removed, one of the diagonals between levels 3 and 4 on the face containing legs A1 and A2 (see Fig. 2) was cut through using a hacksaw. Roughly a 1% frequency reduction was observed in X-sway and torsion frequencies and, as expected, no change was noted in Y-sway.

4. Severed diagonal with hard foundation. The rubber padding was removed and the leg bottoms were bolted directly to the seismic slab, as they were in the Round Robin baseline. Again, about a 1% reduction was observed relative to the undamaged reference (next case).

5. Baseline model on hard foundation. The cut diagonal was rewelded and the configuration thereby returned to its original state.

The natural frequencies for the above configurations are listed at the top of Table 1 and a series of significant comparisons are listed at the bottom of the table. Mode shape results for the test series are shown in Figs. 3, 4, and 5. Figure 3 displays the average level deflections normalized to the corresponding average deck deflection for X-sway and torsion. (Y-sway results are similar to X-sway and are omitted to avoid clutter.) In all cases, the diagonal severance (below level 3) essentially shifts the shapes to the right at level 3 and above. Also, the soft foundation produces a relatively large translation and rotation of the shape. Finally, the added deck mass, even though it provided the biggest shifts in natural frequencies (see Table 1), produced only a relatively small shift of mode shape to the left. Figure 4 displays selected results for the Flexibility Parameters, which emphasize slopes of deflection shapes. Omitted for clarity are results for Y-sway and added mass which, except for scatter, overlay the baseline X-sway curves.

For another comparison, Fig. 5 presents the difference in Flexibility Parameters for the three configuration comparisons identified in Table 1. The horizontal bars for sway show the spread between the soft and hard foundation or between the X and Y directions, as labeled. The key observations from Fig. 5 are as follows:

1. Diagonal severance produces a strong shift for the bay involved only in the affected sway direction and in torsion (see short dotted lines in Fig. 5). Relatively little shift occurs for the other bays. Moreover, the magnitude of the shifts due to severance is practically independent of the degree of softness of the foundation (barring foundation change at the same time). (This was not observable for torsion, only because the data were unavailable for the hard foundation case with severance.)

2. Major foundation softness increase (8 to 9% reduction in sway frequencies) produces a strong shift for all bays in both sway directions (see solid line in Fig. 5a), which is clearly distinguishable from the shift pattern due to severance. The shift for torsion in this case is generally small; this is believed to be due to the relatively slight foundation change for torsion (as evidenced by the relatively small change in frequency, see Table 1).

3. Deck mass increase (14 to 15% reduction in sway frequencies and 9% in torsion frequency) yields much smaller shifts in the sway modes than does the foundation change, even though the frequency changes are considerably larger for the mass change (see long dotted lines in Fig. 5).

The overall conclusion is that, from experimental evidence in the laboratory (as well as theoretically), the Flexibility Parameters provide a powerful basis for detecting jacket damage that affects bay shear flexibility. Also, foundation change can be distinguished and mass change can typically be ignored. A corollary conclusion is that Flexibility Parameters can be very useful in general parameter identification studies for structural dynamic mathematical modeling.

AN ANALYTICAL SIMULATION OF OBSERVED SENSITIVITY TRENDS

The very simplified mathematical model shown in Fig. 6 can simulate the basic sensitivity behavior observed in the model testing. In this planar model, the foundation flexibility is idealized as separate shear flexibility A_f and rotational flexibility A_θ. The effective mass M is assumed to be concentrated at the top, a distance H from the foundation, and the i^{th} bay has shear flexibility A_i. The result is a single-degree-of-freedom dynamic model having the stiffness

$$K = (A_0 + A_1 + A_2 + \ldots + A_n + A_f + H^2A_\theta)^{-1} \quad \ldots\ldots(2)$$

The natural frequency is

$$\omega_n = (K/M)^{1/2} \quad \ldots\ldots(3)$$

and the associated mode shape, normalized to unity at the top, is

$$\phi_i = X_i/X_0 = (A_i + \ldots + A_n + A_f + h_iHA_\theta)K \quad \ldots\ldots(4)$$

where h_i is the height of level i above the foundation. Note that the mode shape is independent of mass.

The flexibility parameter for the i^{th} bay is given by

$$\Delta_i = \frac{X_i - X_{i+1}}{X_0 - X_1} = \frac{A_i + \alpha_i H^2 A_\theta}{A_0 + \alpha_0 H^2 A_\theta} \quad \text{..............(5)}$$

where α_i and α_0 are the fractions of the total height H occupied by bays i and 0, respectively.

For the model shown in Fig. 2, it was found that the following parameters yield a rough match of the observed X-sway mode shape: $n = 4$, all $\alpha_i = 1/5$, $A_2 = A_3 = A_4 = A$, $A_1 = 2A$, $A_0 = 45A$; for the hard foundation, $A_f = A_\theta = 0$ and for the soft one, $A_f = 3A$ and $H^2A_\theta = 6A$. When a diagonal is severed in the physical model, it is assumed that the entire shear stiffness of the involved bay face is lost and that the average bay shear flexibility becomes double the intact flexibility. Therefore, the severance of a diagonal in a face of bay 3 is represented by an increased flexibility in the mathematical model of $A_3 = 2A$. The mode shapes for the hard and soft foundation, with and without diagonal severance, are shown in Fig. 7. These shapes are similar to the corresponding measured average X-sway shapes seen in Fig. 3. Moreover, the natural frequency shifts match those for X-sway in Table 1: a 1% reduction for the severed diagonal for both the hard and soft foundation and an 8% reduction from the hard to soft foundation. The Flexibility Parameters are illustrated in Fig. 8 for comparison to the measured ones shown in Fig. 4. It is quite clear that the primitive mathematical model in Fig. 6 roughly simulates the experimentally observed sensitivity trends. It is therefore believed that platform sensitivity behavior can be studied using simple generic models similar to the authors' previous sensitivity studies.[1]

FIELD INVESTIGATIONS

During 1982, the first two field investigations of Flexibility Monitoring were conducted in cooperation with industry on two deepwater Gulf of Mexico platforms. In April, the platform investigated was Shell's Cognac (308m sea depth) during production operation. In December, it was Chevron's Garden Banks (209m sea depth) during drilling operation. The objectives of these investigations were to provide realistic field experiences in which to assess the practicality and potential accuracy of Flexibility Monitoring and to gain experience as a basis for future refinements. Of critical importance are the hardware and software aspects necessary to achieve high quality data and accurate Flexibility Parameters.

The instrumentation and deployment systems utilized were developed for environmental data gathering and for mathematic model verification purposes; the development on Cognac was by the Shell Development Company and on Garden Banks by the Chevron Oil Field Research Company. Basic ingredients for practical Flexibility Monitoring studies were present: (1) instrument chutes on corner legs, (2) accelerometer packages deployable at any position down the chutes, and (3) accelerometers properly disposed on a deck. All accelerometers were of the force-balance type (also known as servo-rebalance), which is the most suitable for the necessary precise measurements.[4] Special test equipment furnished by The Aerospace Corporation for real-time Flexibility Monitoring investigations included the same summing circuits and FFT signal analyzer previously utilized in the special follow-on testing of the Round Robin model. It was assumed that, in a field investigation, necessary horizontal accelerometers sensing parallel to the platform geometric axes would be positioned at corners of the jacket and deck. As discussed below, this expectation was not met on Cognac, but was on Garden Banks.

On Cognac, dry chutes were present on all four corners and extended to a depth of 75m, approximately one quarter of the way from the sea surface to the mudline, with access from the +4m walkway. Deployment was limited to one package per chute. Each package contained a triaxial set of accelerometers. Unfortunately, the planned real-time measurements of Flexibility Parameters could not be accomplished because the accelerometers within the packages did not parallel the geometric axes of the platform. On the corners of one broadside face, the accelerometer axes were parallel to the leg batter axes, such that the near lateral accelerometers were parallel to a broadside and an end-on face of the jacket. In the other broadside face, the departure from desired orientations was more serious in that the lateral axes were rotated about the batter axis by some 15° out of the jacket face planes. As a consequence, the quantitative results were limited to an assessment of data quality; specifically, coherence evaluations. Nonetheless, the experience was a valuable contribution to the learning process for practical application of Flexibility Monitoring.

On Garden Banks, the chutes were present on three corners and extended to about the top of the skirt piles at a depth of 179m. Two packages could be positioned independently within each chute. Moreover, the biaxial lateral accelerometers in each package were oriented so that their sensitive axes paralleled the platform lateral geometric axes. It was most convenient to deploy two packages down the two diagonally opposite corner chutes and not use the third chute at all. The upper two packages were positioned at the top level, and the lower two at the bottom level, of a bay whose Flexibility Parameters were measured in real-time with normalization against the deck average deflections, rather than below deck shear deflection. The relation of the below deck average shear deflections to deck average deflections was also measured to permit correction of the Parameters to the basic normalized form. The real-time measurements were restricted to the two fundamental sway directions (at about 1/3 Hz) for the first bay below the +4m level and for the two lowest bays above the top of the skirt piles. In addition, average sway motions at some of the intermediate levels were also measured. The FFT resolution was 0.025 Hz, with a Hann window and 30 overlapped (by 50%) averages, requiring 10-1/3 min of data.[5]

On both structures, relative end-to-end calibrations were performed by co-locating accelerometers on a deck with the intent that they sense identical motions in the fundamental modes. Such relative calibration (amplitude and phase) were obtained in real-time at the fundamental sway frequencies. A post-test repeat of the calibrations (two-day interval) was performed on Garden Banks. The deck accelerometers were affixed to a leg and the packages were placed on deck plating about one meter away. The repeatability of the calibrations among the package accelerometers was 0.9% or less and the associated coherences were 0.998 or above. (Such high coherences were also obtained on Cognac in the fundamental sway modes during relative calibrations, as well as when individual underwater accelerometers were measured relative to a deck acceleration.) The repeatability of three of the four deck accelerometers relative to a reference accelerometer in a package was relatively poor, from 1.4 to 6.4%. This poor repeatability is believed to be due primarily to bias error associated with severe platform bumps during the pretest calibrations and to the fact that those bumps were felt differently on a leg versus on a deck plate. The platform bumps were an atypical condition. It is believed that by either avoiding calibration during such bumping or locating all accelerometers on identical structure, coherences of 0.998 are achievable and random errors can be kept below 1% with 95% confidence (requiring at least 40 averages).[5]

The sway Flexibility Parameters on Garden Banks were measured in real-time with coherences of 0.97 or higher with 30 Hanned overlapped averages. This leads to the expectation that the random uncertainty in magnitude is within 4.6% with 95% confidence.[5] Bias errors due to relative calibration errors are roughly proportional to the average deflection at the bay divided by the relative deflection across the bay. For example, when differencing two accelerations, if one has a calibration error of 1% and the actual relative deflection is 10% of their average deflection, then the resulting error in the measured relative deflection will be about 0.01/0.10 or 10%. Thus, the bias error tends to be highest for the uppermost bay and decreases continually as bays approach the foundation. Bias errors due to calibration errors will therefore tend to smoothly distort the Flexibility Parameter distribution. They are unlikely to lead to misinterpretation of bay damage, which is characterized by local change in the distribution. In contrast, random errors (if large enough) can more easily lead to misinterpretation of damage. The allowable random error is a function of the sensitivity desired for the technique. Thus, if it is desired to detect the severance of a diagonal member contributing one-sixth of the bay average shear stiffness, it is judged necessary to keep the rms random error less than about 4% so that the error with 95% confidence does not exceed 8% or half the resulting percentage change in average shear stiffness. As mentioned above, this degree of accuracy was bettered on Garden Banks.

CONCLUSIONS

The laboratory and field testing to date strongly suggest that the method can be developed to become viable for cost-effective contribution to an overall structural inspection program. It is therefore deserving of industry support. It appears to have the necessary attributes of sensitivity to jacket or foundation flexibility change, insensitivity to mass change, practicality of implementation on an operating platform, and long-term stability.

RECOMMENDATIONS

Additional offshore experiments and analytical studies are needed to further explore and demonstrate the capability of Flexibility Monitoring. Major areas of offshore experimental investigation are (1) optimization of equipment and procedures, (2) repeatability of results over time, and (3) demonstration of damage detection capability. A major limitation is the availability of candidate platforms having suitable instrument chutes and instrumentation. The installation of appropriate chutes on new stuctures is encouraged. It is recommended that criteria be developed for standard dimensions and other installation aspects of chutes so that common instrumentation can be developed and so that the suitability of the chutes for Flexibility Monitoring is assured. To achieve a demonstration of damage detection capability at relatively modest cost, it is recommended that Flexibility Monitoring be evaluated in conjunction with demolition of a platform, employing divers to place the instrument packages and to cut members (blind to the evaluators). It is further recommended that analytical studies be conducted using three-dimensional generic mathematical models, to further explore the sensitivity aspects of the approach.

ACKNOWLEDGMENTS

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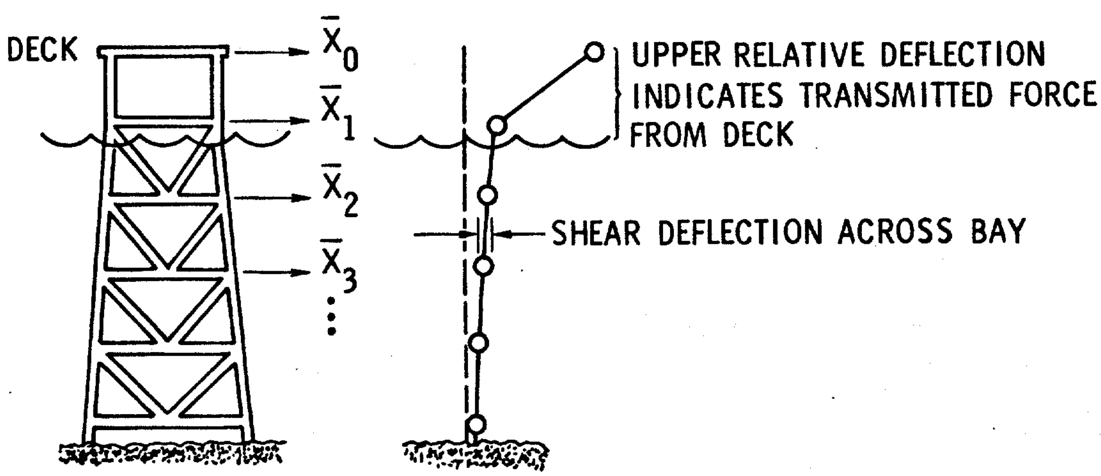
TABLE 1 - CONFIGURATIONS AND NATURAL FREQUENCIES

Configuration	Natural Frequency (Hz)		
	X-Sway	Y-Sway	Torsion
A. Hard foundation	19.8	19.1	31.6
B. Hard foundation + severed diagonal	19.7	19.1	31.4
C. Soft foundation	18.1	17.5	31.2
D. Soft foundation + severed diagonal	17.9	17.5	30.9
E. Soft foundation + added deck mass	15.6	14.8	28.4
Comparisons	**Percentage Changes**		
From baseline to severed diagonal			
Hard foundation (A→B)	- 1	0	-1
Soft foundation (C→D)	- 1	0	-1
From hard to soft foundation (A→C)	- 9	- 8	-1
From original to added deck mass (with soft foundation; C→E)	-14	-15	-9



FLEXIBILITY = DEFLECTION/FORCE

$$\text{FLEXIBILITY PARAMETER} = \frac{\text{BAY DEFLECTION}}{\text{UPPER RELATIVE DEFLECTION}}$$

Fig. 1—Conceptual basis for Flexibility Monitoring.

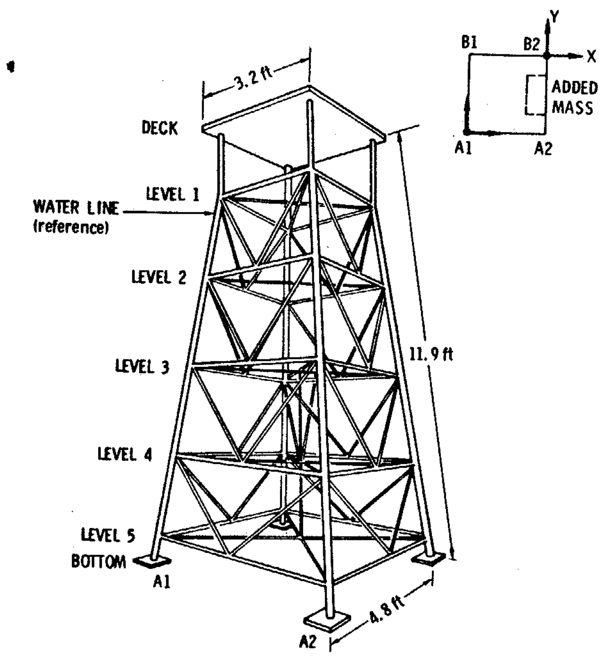


Fig. 2—Round robin model.

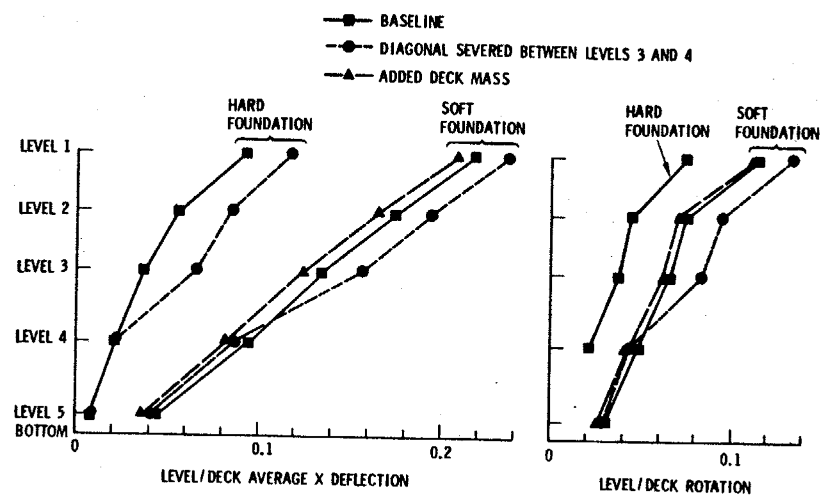


Fig. 3—Normalized mode shapes for X-sway and torsion modes.

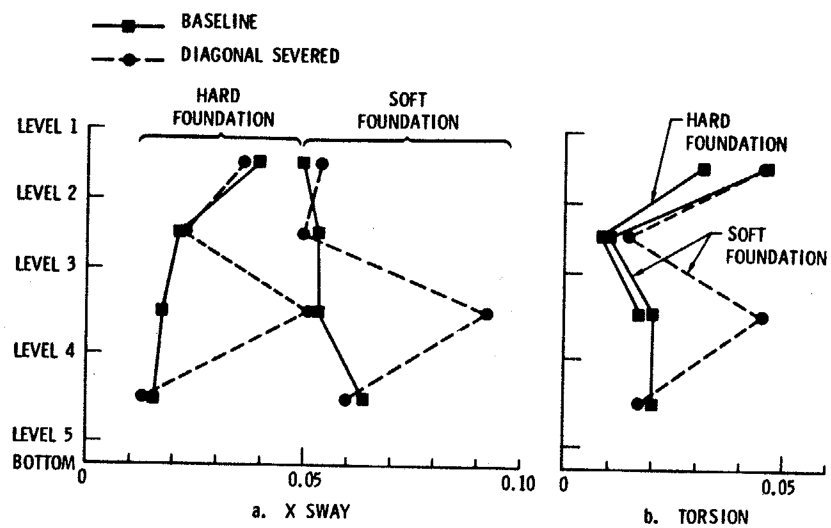


Fig. 4—Flexibility Parameters.

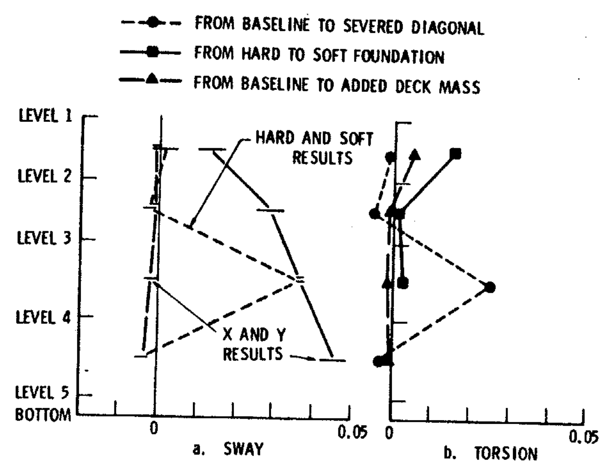


Fig. 5—Differences in Flexibility Parameter.

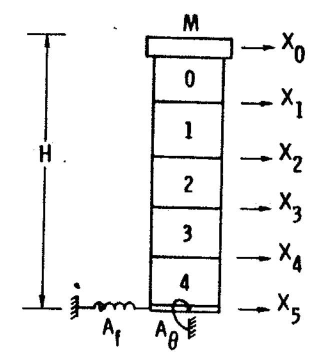


Fig. 6—Simplified mathematical model.

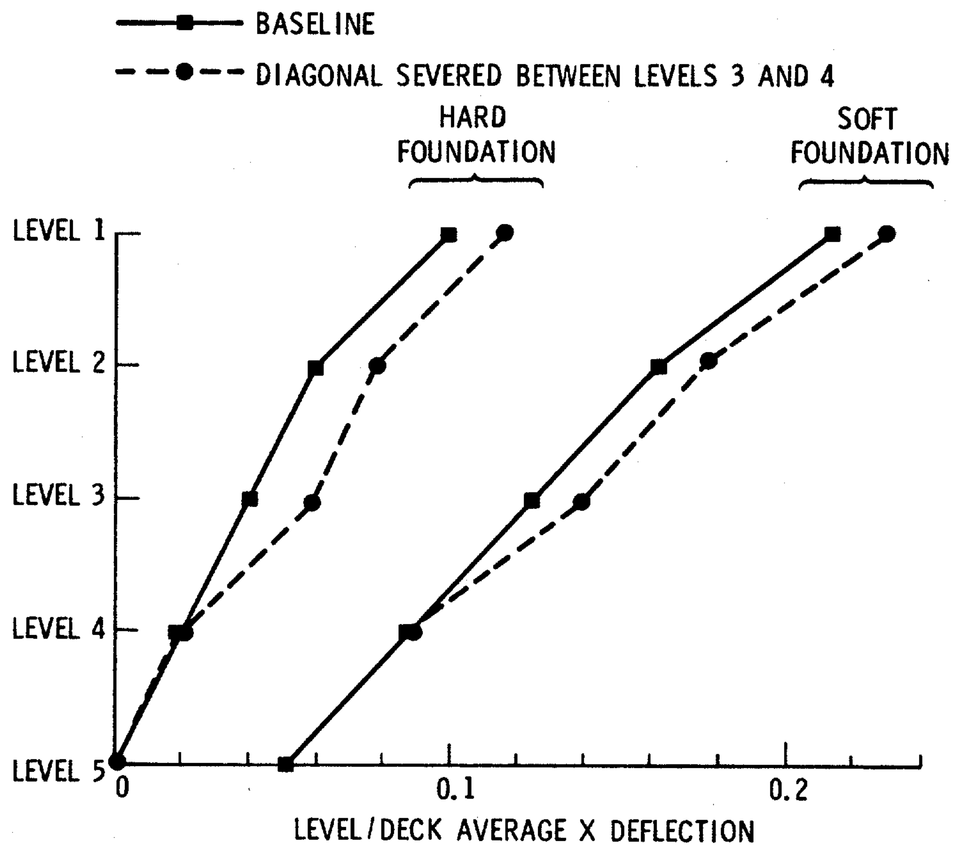


Fig. 7—Analytical mode shapes.

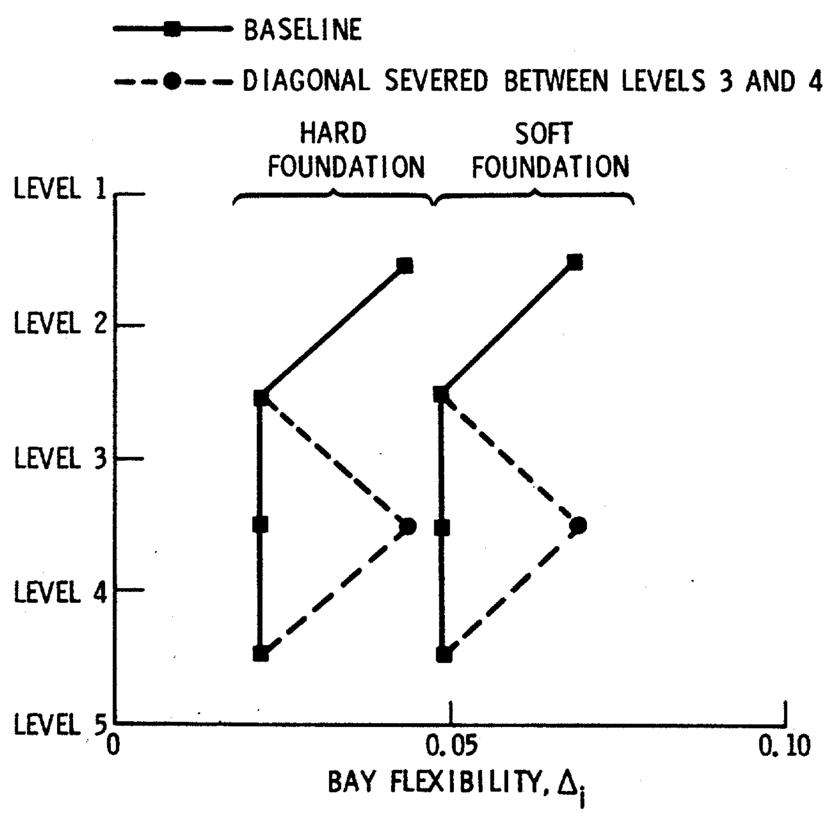


Fig. 8—Analytical Flexibility Parameters.